Classical Optics in a New Light: Flat Photonics based on Metasurfaces I

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Mikhail Kats  Romain Blanchard  Guillaume Aoust
• Introduction: Bulk optics and Flat optics

• Light propagation with phase discontinuities
  ➢ Generalization of the laws of reflection and refraction
  ➢ Experiments with metasurfaces

• Flat optical components
  ➢ Flat lenses
  ➢ Quarter-waveplates
  ➢ Vortex plates
  ➢ New coatings and filters
  ➢ Wavefront engineering of lasers
Recent developments in field of optics

Metamaterials and Transformation Optics

Propagation of light is controlled by considering artificial 3D materials with designed permittivity and permeability.

What can we do in 2D? “metasurfaces”
Planar technology is central to Integrated Circuit technology ( $ 300 B industry): Technology platform.

Because of fabrication complexity 3D optical materials (metamaterials etc.) don’t have a good chance of a major technology impact at optical wavelengths.

Lessons of photonic (PC) crystals: beautiful physics but very limited technology penetration: hard to make and for 2D PC devices there is the problem of coupling efficiency

So we should look at what we can do in 2D with surfaces:

**METASURFACES FOR FLAT OPTICS**

Optically thin engineered metasurfaces for Wave Front Engineering (phase control):

Refractive index is not a useful quantity when we think about metasurfaces: local phase and amplitude control of light along the surface using optical antennas

New class of flat, compact and broadband components: lenses, polarizers, filters, Optical phased arrays for high speed wavefront control
Conventional optical components rely on propagation effect

Camera lens (cross-section)  Quarter-wave plate

Propagation phase: \[ \int_A^B k \circ n(r) dr \]  Bulk birefringence: \[ d |n_e - n_o| = \lambda/4 \]

What if we introduce in the path a distribution of phase jumps?
Light propagation with phase discontinuities

\[ A \sin(\omega t - k_x x) \quad A \sin(\omega t - k_x x + \Phi_{\text{jump}}) \]

What if could have a spatial distribution of different phase discontinuities along the entire interface? → can make any desired wave front!

How? → Optically thin array of sub-wavelength spaced antennas

Huygens principle
Fermat’s principle:
Imposing the stationary phase conditions:
\[ k_o n_i dx \sin(\theta_i) + (\Phi + d\Phi) = k_o n_t dx \sin(\theta_t) + \Phi \]

Suppose interface with a constant gradient of phase delay \( d\Phi/dx \)

Generalized Snell’s law
\[ \sin(\theta_t) n_t - \sin(\theta_i) n_i = \frac{\lambda_o}{2\pi} \frac{d\Phi}{dx} \]

Similarly for reflection:
\[ \sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_o}{2\pi n_i} \frac{d\Phi}{dx} \]
Light propagation with phase discontinuities

Generalized reflection and refraction of light
Meta-interface for demonstrating generalized laws

- Optically thin: 50nm
- Subwavelength phase resolution: $\sim \lambda/5$
- Instant imprinting of a linear phase distribution

N. Yu et al., Science 334, 333 (2011)
V-shaped antenna I

This antenna has a broader resonance and greater phase coverage than a linear one.
V-Shape Antenna II

Original

Mirror structure

Symmetric mode

Antisymmetric mode

\[ E_{\text{out}} = A_s e^{j\varphi_s} + A_a e^{j(\varphi_a)} \]

\[ E_{\text{out}} = A_s e^{j(\varphi_s+\pi)} + A_a e^{j(\varphi_a+\pi)} \]

\[ 0 \quad \pi/4 \quad 2\pi/4 \quad 3\pi/4 \quad 4\pi/4 \quad 5\pi/4 \quad 6\pi/4 \quad 7\pi/4 \]

✓ uniform amplitude
✓ 2\pi phase coverage
Polarization properties of the anomalous beam

Experiments: Normal incidence

\[ \Gamma = 11 \mu m \]

antenna orientation: \( \beta = 45^\circ \)

\[ |2\beta - \alpha| = 90^\circ - \alpha \]

\[ \theta_t = \sin^{-1}(\lambda/\Gamma) \]
Anomalous refraction

The antenna operate as secondary scatterers with a tailorable phase response, re-directing a normally-incident beam away from the normal.

Arrays of Au antennas on Silicon

- Uniform scattering amplitude
- Controlled phase responses between 0 to $2\pi$
Schematic experimental set up

\[ \theta_i \]

- **Anomalous refraction**
  - \( \sim 10\% \)
  - \( \sim 20\% \)

- **Ordinary refraction**
  - \( \sim 20\% \)

- **Anomalous reflection**
  - \( \sim 20\% \)

- **Ordinary reflection**
  - \( \sim 40\% \)

- **Incidence**
  - \( \lambda = 8 \mu m \)

- **Antenna absorption**
  - \( \sim 10\% \)
Experimental results: anomalous refraction

- Linear gradient of phase discontinuities creates modified refraction and reflection behavior

\[ \theta_t = \text{arcSin}(- \frac{\lambda_0}{\Gamma}) \]

Broadband operation

\[ \theta_t = \sin^{-1}\left( -\frac{\lambda_o}{\Gamma} \right) \]

\( \Gamma (\mu m) \)
- 11
- 13
- 15
- 17

Intensity (a.u.)

Angle of refraction \( \theta_t \) (degree)

Shalaev group
Anomalous reflection and refraction

**Reflection**

- Negative reflection
- Nonlinear relationship
- Critical angle for reflection

**Refraction**

- Negative refraction
- New total internal reflection angles
Out-of-plane refraction and reflection

\[ \int \varphi(\vec{r})d\vec{r} = \int \varphi(\vec{r})d\vec{r} \]

\[ \begin{align*}
  k_{x,t} &= \frac{d\Phi}{dx} \\
  k_{y,t} &= k_{y,i} + \frac{d\Phi}{dy}
\end{align*} \]

- Refraction and reflection out of the plane of incidence!

F. Aieta et al. Nano Letters 12, 3 (2012)
Quarter wave plate

Design based on phased optical antennas

- Background free
- Arbitrary orientation of incident E-field vector
- Broadband operation: quarter-wave plate $\Delta \lambda = 5-14 \mu m$
Creating beams with arbitrary polarization

The two rows of antennas in the unit cell create the two orthogonal polarized components with 90 degree phase difference.

\[ d = \frac{\Gamma}{4} \leftrightarrow \Psi = \frac{\pi}{2} \]
• Ultra-flat devices that are broadband and high-purity: 5-11 \mu m with \sim 99\% of the light in the desired polarization
Why Lenses are thick? Can we make a flat lens?
A spherical lens focuses the rays coming parallel to a single point at distance \( f \). This can be seen as the effect of a modulation of the phase imparted to the light from the spherical shape of the lens.
The phase distribution can be calculated simply imposing constructive interference at the focal point of all the rays hitting the interface. 

To focus at a certain focal $f$ the interface must compensate for the distance of every point from a spherical surface centered in the focus and with radius $f$. 

$$
\varphi_L(x, y) = -\frac{2\pi}{\lambda} \sqrt{(x^2 + y^2)} + f^2
$$
To focus at a certain focal $f$ the interface must compensate for the distance of every point from a spherical surface centered in the focus and with radius $f$.

$$\phi_L(x, y) = \frac{2\pi}{\lambda} P_{LS} = \frac{2\pi}{\lambda} \left( \sqrt{x^2 + y^2} + f^2 - f \right)$$

No spherical aberration and large numerical aperture

F. Aieta et al Nanoletters, Aug. 15, 2012 (on line)
Monochromatic Aberrations

Wavefront = Envelope of Secondary Waves with radii
\[ R(x) = \frac{\lambda}{2\pi} \times \phi(x) \]

High N.A. = 0.8

\[ \sin \theta_i \neq \theta_i \]
Flat Lens

Phase Shift [degree]

Amplitude [normalized]

# Antennas

1 2 3 4 5 6 7 8

1.55 μm

laser

pol pin det
Flat Lens

Calculation

Measured xz cross section

Measured yz cross section

Lens f = 6cm

Lens f = 3cm

Calculation

Experiment

High N.A.

\[ r = 0.9 \text{mm} \]

N.A. = 0.015

N.A. = 0.77
Thin film interference revisited...

- **Large optical absorption in ultra-thin layers**
  - Behavior of lossy dielectrics and metals with finite conductivity
  - Optical interference effects in highly-absorptive media

- **VO$_2$-based tunable perfect absorber**
  - A tunable disordered metamaterial: VO$_2$
  - Implementation of tunable perfect absorber
  - Experiments, calculations, and discussion

- **Critically coupled resonators**
  - Concept
  - Implementations in literature
Thin film optical coatings

- Last half century: a lot of work on optical coatings and filters using thin film interference effects

- Nearly all thin film optical coatings use dielectric layers with thickness on the order of a wavelength, where the dielectrics have low optical loss
Thin film interference: Coloring by reflection resonance in $\lambda/4$ thick films

The incident light is white light. Light reflecting from the top surface of the film undergoes a 180° phase change. This is equivalent to shifting the wave by half a wavelength.

Thickness of the oil film is $1/4$ of the wavelength of red light in oil.

Light reflecting from the bottom surface of the oil film has no phase change, but it travels an extra distance of half the wavelength of red light. Red light reflected from the top surface interferes constructively with red light from the bottom surface, so the film looks red. Light of other colors experiences destructive interference.
Nanometer thickness optical coatings

- We were able to make “blue gold”, “pink gold”, and other colors utilizing 5-20 nm semiconductor layers → much thinner than $\lambda/4$

*Kats et al, Nature Materials (published online, 2012)*
Reflection phase shifts at dielectric-dielectric interfaces are either 0 or $\pi$ and reflection from an ideal metal has $\pi$ phase shift.

Metals with finite conductivity and lossy dielectrics have “weird” interface reflection phase shifts (i.e., not 0 or $\pi$).

- Resonances can exist for films significantly thinner than $\lambda/(4n)$.
- To achieve high absorption, the dielectric must be very lossy.

- Punchline: it is possible to have an absorption resonance at specific wavelength (and even a perfect absorber) resulting from coherent effects in a system involving an ultra-thin, highly-lossy layer.
- This leads to coloring.
Absorption resonances lead to coloring

- Lossy dielectric → Germanium
- Lossy metal → Gold
Why was this simple geometry be overlooked?

1. Coherent effects are not discussed in highly-lossy materials
2. Without lossy materials, reflection phase shifts are fixed to either 0 or \( \pi \)

Lossy materials introduce nontrivial reflection phase shifts (\( > \pi \))

- Resonant cavities can be made thinner than \( \lambda/4 \)
- Short propagation lengths allow the use of highly absorbing media
Patterning ultra-thin coatings to create images, labels, etc

The difference between blue and purple, and purple and pink is only ~4 nm of germanium (~ 8 atomic layers)!

*Kats et al, Nature Materials (published online, 2012)*
Our experimental system comprises a thin (180nm) film of vanadium dioxide (VO₂) on sapphire

- VO₂ serves as highly-absorbing layer
- Sapphire is highly-reflecting due to phonon activity in the IR
Why sapphire?

- In the IR, what reflectors give us non-trivial optical phase shifts upon reflection?

\[ n_{23} = \frac{\tilde{n}_2 - \tilde{n}_3}{\tilde{n}_2 + \tilde{n}_3} \]

- At \( \lambda = 12\mu m \), conventional metals do not work
  - \( n_{Au} \sim 15 + 60i, n_{Fe} \sim 6 + 40i \), etc \( \rightarrow \) all pretty much PEC-like..
  - **Sapphire (crystalline \( \text{Al}_2\text{O}_3 \)) fits the bill!**

\( \rightarrow \) Multi-phonon activity in Sapphire

\( \rightarrow \) **At** 11.75\( \mu m \), \( n \sim 0.1 + 0.8i \)

Vanadium dioxide (VO$_2$)

- VO$_2$ is a correlated metal oxide which experiences phase change upon heating to past ~70 °C (reversible, but with hysteresis)

- Conductivity changes by >10,000 from the insulating to conducting state

VO$_2$ in the transition region

- What happens in the transition region of VO$_2$?

Nanoscale islands of metal-phase VO$_2$ begin to form within a background of dielectric-phase VO$_2$, which then grow and connect.

- The mixture can be viewed as a disordered, natural metamaterial
- The ratio of co-existing phases can be controlled $\rightarrow$ tunable medium

Tunable perfect absorber

- Temperature control of VO$_2$ allows us to significantly change the sample reflectivity!

- Reflectivity tuning from $\sim$80% to 0.25% at 11.6$\mu$m
  → on off ratio of more than 300
  → entire effect due to just 180nm of VO$_2$ on sapphire

**Graph:**
- Reflectivity vs. Wavelength (μm) for different temperatures:
  - 297K
  - 343K
  - 346K
  - 347K
  - 348K
  - 351K
  - 360K

*Kats et al., APL 101, 221101 (2012)*
Hysteresis

Reflectivity at $\omega = 11.6$ m

Increasing T
Decreasing T

Reflectivity at $\lambda_o = 11.6$ $\mu$m

Temperature (K)
Tunable perfect absorber

- Used textbook 3-layer equation

\[ r = \sum_{m=0}^{\infty} r_m = \frac{r_{12} + r_{23} e^{2i\beta}}{1 + r_{12} r_{23} e^{2i\beta}} \]
\[ \beta = \frac{2\pi}{\lambda_0} \tilde{n}_2 h \]

Reflectivity vs. Wavelength (μm) for different temperatures:
- 297K
- 341K
- 342K
- 343K
- 343.6K
- 346K
- 360K

Experiment setup:
- FTIR source
- TO MCT detector
- Objective
- VO₂
- Sapphire
- Temp. controlled plate
Understanding the $R = 0$ condition

- Using only 3-layer equation
  \[ r = \sum_{m=0}^{\infty} r_m = \frac{r_{12} + r_{23} e^{2i\beta}}{1 + r_{12} r_{23} e^{2i\beta}} \]
  and experimental material data

- Fix $h = 180\,\text{nm}$, $\lambda = 11.75\,\mu\text{m}$, sapphire substrate

- VO2 complex-index trajectory as a function of temperature goes through perfect-absorption condition

- The minimum is very broad in $n$-$k$ space, so the condition is insensitive to small changes in material composition, defects, incident angle etc.
Perfect absorber: angle-dependent spectra

- Calculation of the angle-dependent reflectivity spectra

- Reflectivity remains under 0.01 for incident angles of 0° ~ 30° for both s- and p-polarization
  - Striking for a thin-film interference effect
  - Useful for capturing large fraction of incident light
Transmission line or light path terminated by a resonator

Reflectivity \( \Gamma = \frac{s_-}{s_+} = \frac{(1/\tau_e) - (1/\tau_0) - j(\omega - \omega_0)}{(1/\tau_e) + (1/\tau_0) + j(\omega - \omega_0)} \)

When \( \omega = \omega_0 \) and \( \tau_e = \tau_0 \), there is no reflection, and the resonator is said to be critically coupled.

Hermann Haus, *Waves and Fields in Optoelectronics*
Critical coupling

\[ \Gamma = \frac{s_-}{s_+} = \frac{(1/\tau_e) - (1/\tau_0) - j(\omega - \omega_0)}{(1/\tau_e) + (1/\tau_0) + j(\omega - \omega_0)} \]

Critical coupling diagram

When \( \omega = \omega_0 \) and \( \tau_e = \tau_0 \), there is no reflection, and the resonator is said to be critically coupled.

Hermann Haus, *Waves and Fields in Optoelectronics*
Critically coupled resonators in optics


Bulovic et al (1996)


Miller et al (2012)

Giessen et al (2010)

Gold + 15 nm of Ge

Equivalent material

\[ \theta = 0 \degree \]

\[ \theta = 40 \degree \]

\[ \theta = 80 \degree \]

\[ \theta = 0 \degree \]

\[ \theta = 40 \degree \]

\[ \theta = 80 \degree \]

“Metamaterial” equivalent

Graphs showing reflectivity as a function of wavelength for different angles and polarizations.
Conclusion

- Introduced critically coupled resonators
- Demonstrated existence of large optical interference in ultra-thin, highly-absorptive films
- Demonstrated a tunable perfect absorber in the infrared based on VO$_2$ and sapphire
- Extended the concept to visible using germanium films on gold substrates

Kats et al, APL 101, 221101 (2012)
Perspectives: ultra-thin optical coatings

- Coloring of metals
  - Smooth and rough metals can be colored by application of ultra-thin, highly-absorbing films

- Modifying reflectivity for optical applications
  - Very black surfaces
  - Reshaping ultra-fast pulses

- Patterning colors
  - New, ultra-flat, single-material labels and patterns

- Harnessing the absorption
  - Ultra-thin angle-insensitive photodetectors, solar cells, etc
  - Can use semiconductors or semiconducting polymers
Flat optics

- New class of flat, compact and broadband components: lenses, polarizers, filters,
  High speed tunable phased array for real-time wavefront control
- Lithography: from Optical to Nanoimprinting and Soft Lithography

Non-Invasive Imaging for Biomedical Application

Major opportunity in Midir due to poor refractory materials
Thank you!